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Spectral Lines from Rotating Neutron Stars

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ABSTRACT

The line profiles from rotating neutron stars are affected by a number of relativistic processes such as Doppler boosts, strong self-lensing, frame-dragging, and the differential gravitational redshift arising from the stellar oblateness. In this *Letter*, we calculate line profiles taking into account the first two effects, which is accurate for rotation rates less than the breakup frequency. We show that the line profiles are not only broadened and weakened but are also significantly asymmetric, and allow for an independent measurement of both the mass and the radius of the neutron star. Furthermore, we investigate the case when a fraction of the neutron star surface contributes to the emission and find that the line profiles are typically doubly peaked. We discuss the implications of our results for searches for line features in the spectra of isolated neutron stars and X-ray bursters. We finally assess the systematic uncertainties introduced by the line asymmetry in inferring the compactness of neutron stars from the detection of redshifted lines.

Subject headings: relativity — stars: neutron — X-ray: stars

1. Introduction

Thermal emission from the surface of a neutron star carries signatures of its strong gravitational field, which become apparent in observations of both its spectral and timing properties. Such measurements, therefore, can be used in principle to infer the masses and radii of neutron stars. Over the past three decades, multiple attempts have been made to constrain the stellar equation of state using observations of the thermal emission from bursting (Lewin, van Paradijs, & Taam 1995), quiescent (e.g., Rutledge et al. 1999), or isolated neutron stars (e.g., Pons et al. 2002; Braje & Romani 2002), the X-ray pulse profiles of rotationally powered pulsars (Page 1995; Pavlov & Zavlin 1997), the high amplitudes of oscillations observed during thermonuclear bursts (Nath, Strohmayer,

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& Swank 2001), and the frequencies of observed quasi-periodic oscillations (Miller, Lamb, & Psaltis 1998).

Of all the possible methods of measuring the radius of a neutron star or a mass-radius combination, the one that suffers the least from systematic uncertainties and measurement errors is using the gravitational redshift of atomic spectral lines. For a slowly rotating, spherically symmetric neutron star, the gravitational redshift gives directly the stellar compactness (i.e., the ratio $R_{\rm NS}/M_{\rm NS}$). This method has received a lot of attention recently with the launch of X-ray telescopes with high spectral resolution (such as *Chandra* and *XMM-Newton*) and the discovery of thermal emission from nearby, isolated neutron stars (see Becker & Pavlov 2002 for a review). A number of observations of neutron stars have already been carried out, which yielded a potential detection of broad, redshifted absorption lines from the pulsar 1E 1207.4–5209 (Sanwal et al. 2002; Mereghetti et al. 2002). Other observations of isolated neutron stars have typically resulted in featureless X-ray spectra (e.g., Paerels et al. 2001; Drake et al. 2002; Marshall & Schulz 2002).

Apparently, not all targets are created equal. The detection of atomic spectral lines in X-rays requires both heavy metals to be present in the neutron-star atmosphere and the surface layers to have high temperatures for significant thermal emission to be generated. These two requirements can be met most easily in either neutron stars that are young or in ones that are weakly magnetic and accreting steadily from a binary companion. Young neutron stars emit thermally the heat released during their formation. They may also possess heavy-element atmospheres if significant light-element fallback did not occur during the supernova: their short lifetimes and strong magnetic fields render unlikely a significant accumulation of hydrogen rich material from the interstellar medium that could suppress atomic lines. In the case of bursters, the heavy elements in their atmospheres are continually replenished by accretion and the thermonuclear flashes provide large amounts of thermal energy.

Both types of neutron stars that are prime candidates for the detection of spectral lines are fast rotators. (We do not consider here magnetars, for which the presence of ultrastrong magnetic fields introduces large uncertainties in calculating the rest energies of atomic lines). The spin frequencies of known pulsars with ages $< 10^4$ yr is between $\simeq 5 - 65$ Hz (see, e.g., Becker & Pavlov 2002); the inferred spin frequencies of bursters is between $\simeq 270 - 620$ Hz (Strohmayer 2001). These high spin frequencies introduce several relativistic effects such as Doppler boosts, strong self-lensing, frame-dragging and differential gravitational redshift arising from the stellar oblateness. All of them alter the line profiles observed at infinity.

In this *Letter*, we show the effects of relativistic Doppler boosts and strong gravitational lensing on the width and asymmetry of line profiles originating from the surfaces of rotating neutron stars. We then investigate the systematic uncertainties introduced by these effects in inferring the compactness of neutron stars.

2. The Effects of Rotation on the Observed Line Profiles

Neutron stars are the most compact stellar objects and the rotational velocities at their surfaces can reach an appreciable fraction of the speed of light. Therefore, rotational effects on the line profiles originating from the neutron star surface are qualitatively different from the case of a Newtonian slowly spinning star. In particular, the shape of the line profiles observed at infinity is altered in four ways.

First, relativistic Doppler boosts give rise to an asymmetry in the spectral line profiles while broadening them. Second, strong gravitational lensing of surface emission by the neutron star alters the relative contribution of surface elements with different line-of-sight velocities to the line profile. Third, frame dragging in the rotating spacetime of the neutron star affects the photon trajectories and thus the observable surface elements. Finally, the stellar oblateness caused by the rapid spin introduces a difference in the gravitational redshifts of lines that are generated at the rotational equator and at the poles.

In this *Letter*, we use the numerical methods described in Muno, Özel, & Chakrabarty (2002 and references therein) to calculate spectral line profiles taking into account the first two of the effects discussed above. Investigating the latter two requires the calculation of numerical spacetimes for specific equations of state of neutron-star matter and will be addressed in a forthcoming paper. The results presented here are accurate for spin frequencies smaller than the Keplerian frequency at the surface of a neutron star, i.e., less than a few hundred Hz. It is important to note that for larger spin frequencies, the ellipticity of the neutron stars induced by the rotation can be as large as 0.3, depending on the equation of state (Cook et al. 1994), yielding an additional broadening as large as $\simeq 15\%$.

3. Results

In the calculations presented here, we show for clarity emission lines; absorption lines are affected in the same way due to the linear character of the equations. Moreover, for numerical reasons, we assume an intrinsic fractional line width of 0.01, which is much smaller than the Doppler width for the cases shown here. Finally, we assume that the observer is on the rotational equator of the star in order to show the maximum rotational effects.

The line profiles measured at infinity coming from the surface of a $1.4M_{\odot}$, 10 km neutron star are shown in Figure 1 for different values of the spin frequency. As the spin frequency is increased, the lines become weaker and broader, and their peak emission shifts towards larger energies. In this figure, the entire neutron star is assumed to be emitting uniformly.

The asymmetry of the line profiles become more prominent when only a fraction of the stellar surface contributes to the line emission. Such a configuration is likely in the case of young neutron stars, which may have lateral composition and temperature gradients owing to their strong magnetic

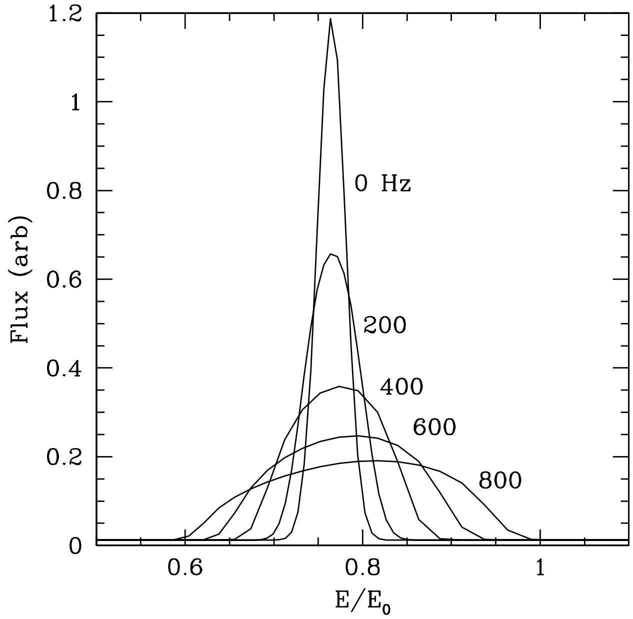

Fig. 1.— Calculated line profiles emerging from a 1.4 $M_{\odot}$, 10 km neutron star, for different values of its spin frequency. Here, the entire neutron star is assumed to be emitting and the observer is at the rotational equator. E_0 is the rest energy of the emission line.

fields. Nonuniform emission is almost certainly relevant also in the case of bursters as indicated by the observations of large amplitude flux oscillations during the thermonuclear bursts (Strohmayer 2001). As Figure 2 shows, in the case of non-uniform emission, phase-integrated line profiles acquire a doubly peaked character, with a brighter blue wing. In this figure, the emitting region, which has an angular radius of 20°, is assumed to be at the rotational equator. This configuration yields the largest separation of the two peaks in the line profile because of the largest line-of-sight velocities. Note that due to the strong gravitational lensing, the two maxima of the doubly peaked profile do not correspond to the line emission at rotational phases $\phi = \pm\pi/2$, where $\phi = 0$ denotes the phase when the center of the emitting region is aligned with the observer. As a consequence, the separation of the peaks is not proportional to $2\gamma\Omega R_{\rm NS}/c$, where γ is the Lorentz factor corresponding to the rotational velocity and Ω is the angular velocity of the neutron star.

The line-of-sight velocities, and thus the separation of the peaks in the phase-averaged line profiles, are also affected by the actual size of the neutron star, for a given stellar compactness. In Figure 3, we show the line profiles measured at infinity that originate from two neutron stars of the same compactness, $R/M = 2.41G/c^2$, but of different radii. Clearly, the larger peak separa-

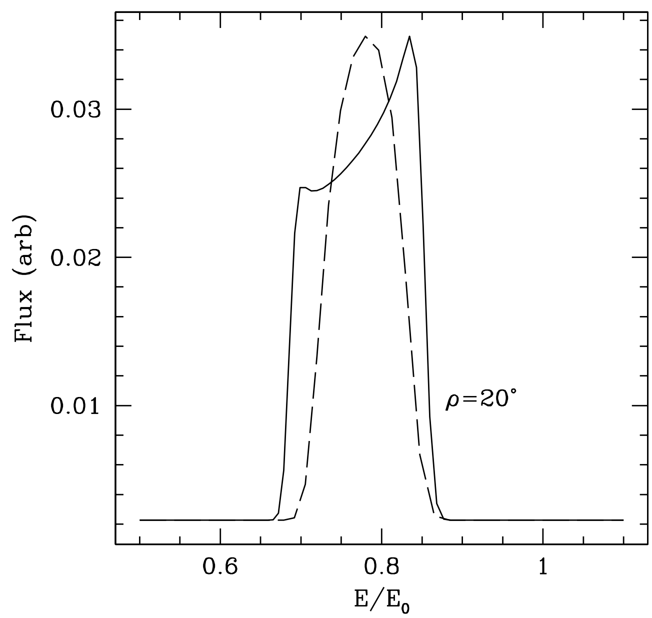

Fig. 2.— The difference in the line profiles observed at infinity when a fraction of (solid line) or the entire neutron star surface (dashed line) is emitting. The quantity ρ denotes the angular radius of the emitting region, which lies on the rotational equator. The spin frequency of the neutron star is 400 Hz. Other parameters are as in Figure 1.

tion corresponds to the larger neutron-star radius. This effect allows in principle an independent determination of the mass and radius (modulo emission geometry) of a neutron star of known spin frequency, given the shape and overall redshift of atomic spectral lines.

4. Discussion and Conclusions

We studied spectral line profiles from rotating neutron stars taking into account the effects of relativistic Doppler boosts and strong gravitational lensing. We showed that the line profiles are broad, as expected, and also significantly asymmetric. The asymmetry becomes more prominent when the surface emission is non-uniform. Our results have a number of implications for the current searches for gravitationally redshifted line features in the spectra of neutron stars.

First, the large widths and suppressed strengths of the rotationally broadened lines make their detection difficult. This may be able to account for the featureless spectra of a number of isolated neutron stars observed with *Chandra* and *XMM-Newton*, such as RXJ 1856–3754 (Braje & Romani 2002; Zavlin & Pavlov 2002). Correspondingly, if narrow line features are detected from rapidly

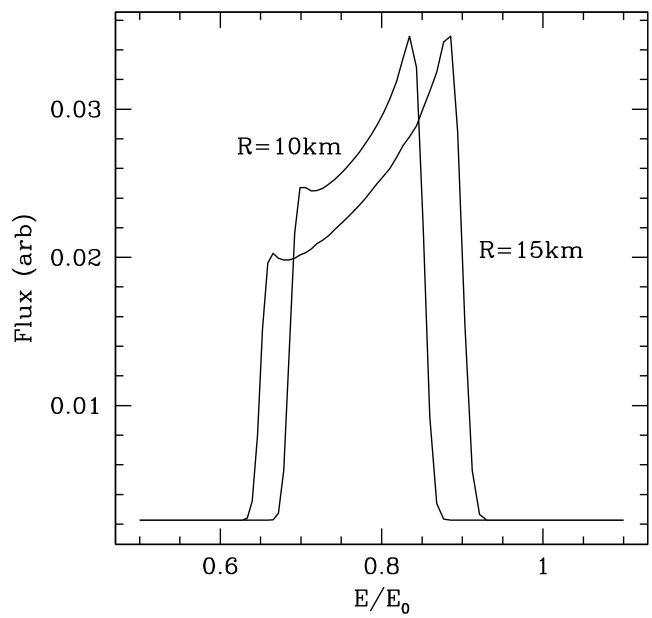

Fig. 3.— The effect of the neutron star radius on the observed line profiles at infinity for stars of the same compactness, $R/M = 2.41G/c^2$. The other parameters are the same as in Figure 2.

rotating neutron stars, e.g., bursters, they could not have originated from the neutron star surface, unless the emission is restricted to the rotational pole. Searches for lines in such sources should take into account these relativistic effects.

Finally, the asymmetry of the line profiles introduces significant systematic uncertainties in measuring the compactness of a neutron star using gravitational redshifts. As an example, Figure 4 shows that if the peak of the line is used in measuring an apparent redshift, the resulting compactness of the neutron star will be significantly overestimated even when the entire surface is emitting. For the inferred spin frequencies of bursters, in the absence of realistic models, the systematic uncertainties can be as large as 10%, which are larger than the 5% accuracy required to distinguish between the different equations of state (Prakash & Lattimer 2000).

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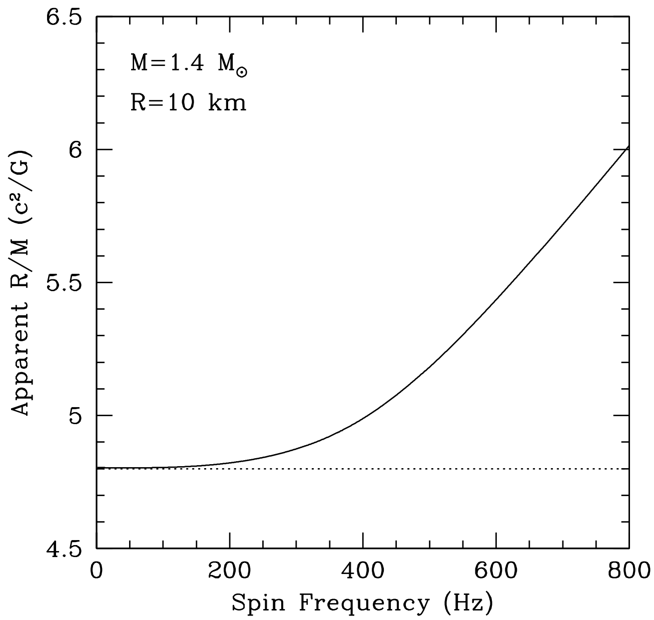

Fig. 4.— Apparent ratio R/M for a neutron star, when the peak of a spectral line is used to infer the magnitude of the gravitational redshift; the dotted line shows the true value of R/M. All the parameters are the same as in Figure 1.

REFERENCES

Becker, W., & Pavlov, G. 2002, in The Century of Space Science (astro-ph/0208356)

Braje, T. M., & Romani, R. W. 2002, ApJ, in press (astro-ph/0208069)

Cook, G. B., Shapiro, S. L., & Teukolsky, S. A. 1994, ApJ, 424, 823

Drake, J. J., et al. 2002, ApJ, 572, 996

Lattimer, J. M. & Prakash, M. 2001, ApJ, 550, 426

Lewin, W. H. G., van Paradijs, J., & Taam, R. 1995 in X-ray Binaries, eds. W. H. G. Lewin, J. van Paradijs, and E. P. J. van den Heuvel (Cambridge: University Press)

Marshall, H. L. & Schulz, N. S. 2002, ApJ, 574, 377

Mereghetti, S., De Luca, A., Caraveo, P.A., Becker, W., Mignani, R., & Bignami, G.F. 2002, ApJ, in press (astro-ph/0207296)

Miller, M. C., Lamb, F. K., & Psaltis, D. 1998, ApJ, 508, 791

Muno, M., Özel, F., & Chakrabarty, D. 2002, ApJ, in press (astro-ph/0204501)

Nath, N. R., Strohmayer, T. E., & Swank, J. H. 2002, ApJ, 564, 353

Paerels, F. et al. 2001, A&A, 365, L298

Page, D. 1995, ApJ, 442, 273

Pavlov, G. G., & Zavlin, V. E. 1997, ApJ, 490, L91

Pons, J. A., et al. 2002, ApJ, 564, 981

Rutledge, R. E., Bildsten, L., Brown, E. F., Pavlov, G. G., & Zavlin, V. E. 1999, ApJ, 514, 945

Sanwal, D., Pavlov, G. G., Zavlin, V. E., & Teter, M. A. 2002, ApJ, 574, L61

Strohmayer, T. E. 2001, Adv. Sp. Res., 28, 511

Zavlin, V. E., & Pavlov, G. 2002, in The Century of Space Science (astro-ph/0206025)